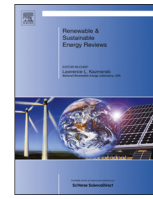
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A review on development of solar drying applications

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ABSTRACT

Drying is an essential process in the preservation of agricultural crops and in industries, such as textile production, dairy processing, cement production, clay brick production, tile production, wood and timber processing, wastewater treatment, and biomass treatment. The energy requirement for drying can be supplied from various sources, namely, electricity, fossil fuel, natural gas, wood, bark forest residual, and solar. Although the use of solar radiation for drying has existed since antiquity, it has not yet been widely commercialized, particularly in the industrial sector. Considering the rapid depletion of natural fuel resources and because of the rising fossil fuel cost, solar drying is expected to become indispensable in the future. Moreover, environmental considerations and damages caused by human beings due to increasing consumption of fossil fuel prompt governments and industries to use renewable energies as a clean and sustainable resource, thus, the use of solar energy for drying. The numerous solar drying applications are classified into two main categories, that is, agricultural and industrial. Many benefits could be exploited from solar energy for drying applications. Solar energy enables the industries and agricultural sectors to modify their energy requirement, improve their energy stability, and increase energy sustainability, which lead to improvement in the system efficiency. We review the role of the drying system in industry and agriculture, the energy consumption capacity, and the availability of the required energy for the products to be dried. In addition, the economical, environmental, and political aspects of using solar dryers are discussed. Special attention is given to industrial drying and in finding opportunities to use compatible dryers for a certain industry. In short, we conduct a comprehensive review of the new approach to use solar energy in industrial drying sector.

Contents

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1. Introduction

Drying is defined as the process of removing the moisture from a product and can be implemented in two stages. In the first stage, the moisture inside the product is brought to the surface and dried in air at a constant rate as water vapor. The second stage involves a slow drying rate, and its process is related to the properties of the material to be dried [1,2]. Drying of different materials, namely, gases, liquids, or solids, can be accomplished by different methods [3]. Drying can be performed using chemical desiccants, by chemical decomposition of the moisture in the stuff, or by freezing using liquids and solids. It can also be performed mechanically by compression, gravity, or centrifugal forces. However, the most common drying method, especially for agricultural products, is thermal drying, which involves simultaneous heat and mass transfer. Thermal drying is used in numerous industrial and agricultural processes. For example, crops such as paddy, oil seed, carrot, herb and spices, and vegetables are dried using heated air. Industrial examples of thermal drying include the drying of bricks, leather, wood and timber, textile, sewage sludge, tea, and dairy products. The energy consumption in such industries is high and depends mostly on both the materials to be dried and the technology used in the process [4].

The sun is the largest available carbon-free energy resource for human being. Many investigations have been conducted to learn how to harvest and apply solar energy as a primary source of energy [5]. Governments and industries all around the world are increasingly looking for ways to prevent the increase in greenhouse gas emissions in their operations. Therefore, they strive to install and use sustainable renewable energy systems to replace those that consume fossil fuels. Therefore, they focus on solar energy because it is the most promising energy source and has many advantages compared with other kinds of energy sources such as fossil fuels. Solar energy causes no negative effect on the environment; hence, its use as one of the main energy sources in the future is expected to increase. Solar drying is particularly applicable in countries located on the sunny belt of the Earth, that is, in regions where the sun radiation is high and the duration of sunshine is long [6]. Generally, solar energy application is categorized into two basic groups. The first main one is the production of electricity using photo cells, which convert directly solar energy to electricity, and the other main group is the thermal application category in which solar drying is included [7,8]. It should be added that in some cases such as concentrated solar power, solar energy is utilized to generate steam in a solar power station and can be categorized in the latter group.

The first use of solar energy for drying purposes dated back to 8000 B.C.; the first solar drying equipment was found in south of France. However, the conventional drying industry started around the 18th century [6]. Solar drying in agriculture, especially in the rural areas in developing countries, is not an option but a necessity because most of these areas do not have access to grid-connected electricity and cannot afford fuel for heaters to provide warm air for drying crops. In such areas, drying methods that employ heaters and fans are not appropriate because of high-energy consumption. Thus, they use traditional open-sun drying. However, this method suffers from many problems. For example, crops are lost because of inadequate drying. Moreover, birds, insects, and rodents encroach on them. Other problems such as fungal attacks, unexpected rain, and adverse weather conditions are common. Hence, the use of solar crop dryers is increasing nowadays, and they have special economic attractions [9]. Dryers using conventional solar air heaters, which have at least a 10-year lifespan, are more efficient and economical than those that consume conventional fuels such as oil or wood, as well as those that use electricity [10]. The application of solar drying in industrial sectors can be investigated for different materials, such as biomass, brick, textile, cement, polymers, paper and allied products, and timber as well as for different processes, such as drying of porous materials, wastewater treatment, and pharmaceutical processes. For instance, the use of solar dryers in wastewater treatment reduces expenses and the duration of the conventional drying process. Another example is solar wood drying, which requires the heating of air supplied by solar heaters in a collector resembling a greenhouse tunnel; the heated air passes through a drying chamber where the wood placed inside the chamber removes the moisture from the product.

Energy consumption is one of the most important considerations in the drying systems. Energy consumption always depends on the type of products to be dried. The use of conventional dryers results in high energy consumption and monetary burden. One disadvantage of solar drying is that solar energy, when used as the only source of energy for drying, is not always available. Thus, hybrid solar dryers, wherein solar energy is combined with other sources of energy, such as fossil fuel, biomass solid fuel, and electrical energy, are used as an alternative solar energy source to address the abovementioned disadvantage. Other disadvantages of solar drying involve political measures that cannot implement solar energy applications in drying systems, although several policies, such as feed-in-tariff (FIT), renewable portfolio standard (RPS), and incentives, are implemented in different countries to encourage the development and application of solar drying technologies. The main objective of the present study is to review the drying process in industrial and agricultural sectors as well as to determine the industrial areas where solar dryers could be utilized to reduce fossil fuel consumption, thus enhancing performance efficiency. The other objective of this study pertains to the environmental, economical, and political aspects.

2. Importance of drying and evaluation of energy consumption

Nowadays, because of the importance of energy that attracted much attention, all industrial sectors regardless of the branch in the industry, must identify more efficient means of energy utilization. Regarding drying, several methods are available to reduce the initial moisture content of a product. For example, water can be removed from solids by mechanical devices such as pressure or centrifuge, whereas in the case of liquids, heat can be reused in a multistage evaporator, which results in appreciable reduction in the overall energy consumption. With regard to the problems presented in Table 1, we must study the drying process

Table 1
Problems encountered in drying [56].

Mode of heating	Conduction, convection, dielectric, radiation
Energy sources	Coal, oil, natural gas, electricity energy, waste materials, solar energy
Pressure	High vacuum (freeze drying), vacuum, atmospheric pressure, high pressure
Scale	From 10 kg/h to > 100 t/h
Type of apparatus	About 100 types of identified dryers are used in the world at present
Source of process control	Boundary layer, inner diffusion, boundary layer with inner diffusion
Size and shape of material	Powder, granules, foil, film, plate extruded material, crystalline, fabric, cardboard, fiber
Initial moisture content	From almost dry (< 1% kg/kg dry material) to full saturation(> 100% kg/kg dry material)
Thermal resistance of the material	From material very sensitive to temperature (< 30 °C) to thermally resistant materials (> 200 °C)
Value of the product	From bulk chemical products (< $70 per ton of dry material) to pharmaceutical products (> $150,000 per ton)

Table 2
Overall pattern of energy usage for drying [56].

Subsector	French industry	British industry		% Due to drying
	Drying (10^9 MJ/year)	Drying (10^9 MJ/year)	Total (10^9 MJ/year)	
Food and agriculture	46.3[a]	35	286	12
Chemicals	8.6	23	390	6
Textiles	1.9[a]	7	128	5
Paper	38.8	45	137	33
Ceramic and building materials	15.7	14	127	11
Timber	7.9[a]	4	35	11
Others	50.3	No data	–	–
Total	≈ 168	128	1103	12

[a] Added thermal energy (tons of oil equivalent) and electricity (GWh), extracted from original data.

Table 3
Typical energy requirements for textile wet-processes, by product form, machine type and process [62].

Product form/machine type	Process	Energy requirement (GJ/t output)
Desize unit	Desizing	1.0–3.5
Kier	Scouring/bleaching	6.0–7.5
J-box	Scouring	6.5–10.0
Open width range	Scouring/bleaching	3.0–7.0
Low energy steam purge	Scouring/bleaching	1.5–5.0
Jig/winch	Scouring	5.0–7.0
Jig/winch	Bleaching	3.0–6.5
Jig	Dyeing	1.5–7.0
Winch	Dyeing	6.0–17.0
Jet	Dyeing	3.5–16.0
Beam	Dyeing	7.5–12.5
Pad/batch	Dyeing	1.5–4.5
Continuous/thermosol	Dyeing	7.0–20.0
Rotary screen	Printing	2.5–8.5
Steam cylinders	Drying	2.5–4.5
Stenter	Drying	2.5–7.5
Stenter	Heat setting	4.0–9.0
Package/yarn	Preparation/dyeing (cotton)	5.0–18.0
Package/yarn	Preparation/dyeing (polyester)	9.0–12.5
Continuous hank	Scouring	3.0–5.0
Hank	Dyeing	10.0–16.0
Hank	Drying	4.5–6.5

accurately because of the important role it plays in terms of energy consumption, which is not an easy task.

Many experimental studies have been conducted in different countries. The results of these studies show that solar dryers are applied extensively in crop [4,6,9,11–13]. Moreover, many studies on the modeling and the dynamics of the drying process have been conducted; these studies focused mostly on the agricultural sector [14–26]. However, simultaneous energy and exergy analyses in the literature review are few [27–30]. All these studies revealed the importance of the drying process in the food industry, agricultural crops, and medical field and in the drying of aromatic herbs. Only a few studies are available on the application of solar drying in the industries, and more research works on drying are needed for different materials and processes. The energy consumption of various drying applications was investigated and confined mainly in the industrial and agricultural sectors. Solar drying can be utilized in different processes, such as textile and clay brick manufacturing, wastewater treatment, food and crop storage, wood and timber drying, biomass solid fuel process, biofuel process, dairy production, and cement production. The evaluation of energy consumption for paddies, pomegranate arils, onions, and spices in the agricultural sector was conducted in this study. Each of the aforementioned items was discussed in detail.

2.1. Industrial drying

Industrial dryers consume a significant portion of the total energy used in manufacturing processes, which is 12% on the average. For instance, the energy used in the drying industry was estimated to be 128×10^9 MJ/year in selected UK areas. The overall pattern of energy consumption in some drying applications in France and the UK is illustrated in Table 2 [31].

As a significant stage in the industry, drying represents a considerable component of the industrial energy use in Canada. Approximately 70% of the total energy in wood manufacturing, 50% in the finished textile fabric production, 27% in the paper industry, and 33% in the pulp production are consumed by the drying process. The energy consumption data for drying were collected and extracted from relatively old sources dating back to 1976 for the US, 1978 for UK, and 1988–1989 for France in the handbook of industrial drying [31,32]. Since then, the energy consumption pattern in the drying system, similar to that in the other sectors of the industry, has changed. For example, in the UK in 1998, approximately 348.6 PJ was used in the drying operation. This amount was equivalent to 17.7% of the countries'' total industrial energy consumption compared with the 11.6% in 1970. Bennamoun [33] reported that in the industrialized countries, between 7% and 15% of the industrial energy consumption has been used in the drying systems.

2.1.1. Textile

A review of the energy use and energy efficiency technologies in the textile industry was conducted, and the contribution of energy consumption in each sector of the textile process was compiled. The textile industry is one of the most complicated manufacturing industries. It uses various substrates, processes, machineries, and components, as well as different methods of

fabric production and finishing process, including the preparation, dyeing, chemical/mechanical finishing, and coating. Hasanbeigi [34] reported many applications of the solar energy in the textile industry, which are mostly for drying and hot water supply. Moreover, the usage of water in this sector is large, that is, to produce 1 t of textile products, approximately 20 m^3 of water is required. This volume of water results in massive amount of wastewater for drying; thus, using solar energy could be an efficient method. The most important factors with the largest share of energy consumption in the textile industry are the following:

- spun yarn spinning;
- weaving;
- wet processing (preparation, dyeing, printing, and finishing); and
- man-made fiber production.

In the wet processing, the high amount of thermal energy used in the both steam and heat forms results in major energy consumption. Table 3 [35] presents the typical energy requirements of the textile wet processing in terms of the product form, machine type, and process. The table shows the amount of energy use for dyeing and drying. Table 4 [36] shows the contribution of each part in dyeing. The drying process also belongs to this stage, whose share is 17.2%. Although the information given in the tables is the average value for the dyeing plants in Japan, it provides an adequate illustration of where the thermal energy is largely used. Moreover, a significant portion of the thermal energy in a dyeing plant is lost through the loss of wastewater, which could have been used to treat the wastewater itself to produce fresh water via the drying process.

2.1.2. Clay brick production industry

The clay brick industry uses the drying systems. Clay is an abundant natural mineral material on Earth. In brick manufacturing, raw clay does not have appropriate properties and characteristics to produce high-quality bricks. Clay has certain plasticity that permits it to be shaped or molded when mixed with water. In addition, it must have sufficient moisture and air-dried strength to maintain its shape after forming. Finally, the clay fuses when subjected to appropriate temperature. Essentially, bricks are produced by mixing ground clay with water, forming the clay into the desired shape, drying, and firing. In ancient times, all moldings were accomplished by hand; however, with the advent of mechanical drying systems in the later part of the 19th century, most bricks produced in developed and developing countries have been machine made. Fig. 1 shows that the manufacturing process has six general phases, and drying is a main stage performed before the firing and cooling stages. After mining, storage, size reduction, screening, and molding or cutting, the bricks are wet, and they contain between 7% and 30% moisture, depending on the forming method. Before the bricks are put in the kiln, they must be dried first at temperature that ranges from approximately 38 °C to 204 °C. The drying time varies with different clays and is usually from 24 to 48 h [37].

Murugesun et al. [38] studied numerically the evaporative drying of a two-dimensional rectangular brick as a conjugate problem. The drying behavior of the brick was predicted using the Navier–Stokes equation to obtain the flow field and the corresponding flow solutions by the continuum approach. They defined the average heat and mass transfer coefficients appropriate to the conjugate problem based on the constant temperature and moisture differentials between the solid and ambient. Their modeling led to a more efficient drying process of the clay bricks.

The brick industry consumes 16% of the total energy in the industries in Iran. The brick industry drying process is a significant stage before the wet clay brick is put into the kiln. Table 5 shows the amount of total energy consumption in the brick industry sector in several countries as reported by the Iranian Fuel Conversation Company, a branch of the National Iranian Oil Company.

Table 4
Breakdown of thermal energy use in a dyeing plant (average in Japan) [63].

Item	Share of total thermal energy use (%)
Product heating	16.6
Product drying	17.2
Waste water loss	24.9
Heat released from equipment	12.3
Exhaust gas loss	9.3
Idling	3.7
Evaporation from liquid surfaces	4.7
Un-recovered condensate	4.1
Loss during condensate recovery	0.6
Others	6.6
Total	100

Table 5
Energy usage for brick industry in some selected countries.

Country	Specific heat energy consumption (MJ/kg brick)	Specific total electrical energy consumption (kWh/t)
Iran	4–8	35–55
Belgium	1.94	43
Germany	1.73	48.8
Denmark	2.16	49.1
Spain	2.14	44
France	2.29	57.6
Greece	2.1	60
Italy	2.11	60
Ireland	2.15	46.7
Netherland	2.45	34.2
Portugal	2.55	43.8
England	2.7	53.6
The mean amount except Iran	2.18	49.4

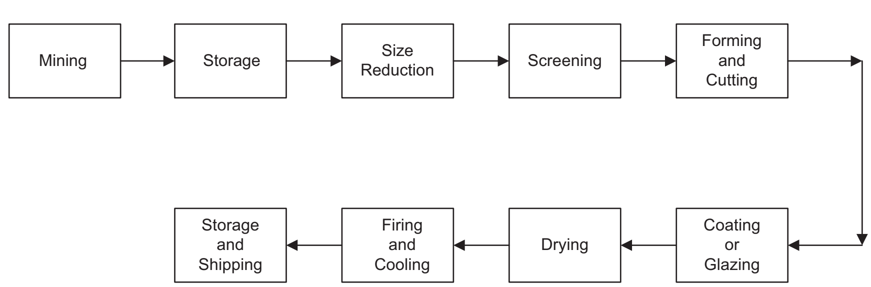


Fig. 1. Clay brick manufacturing process [54].

Table 6
Energy required by different process sections [59].

Process sections	Electrical energy consumption (kWh/t)	
	Dry	Wet
Raw material treatment and crushing	4	3
Mashing	44	10
Fans and coolers	23	25
Dust collector	6	8
Cement milling	45	45
Transportation	8	47
Total electricity required (kWh/t)	130	149
Fuel burned in furnaces (l/t)	112.5	156

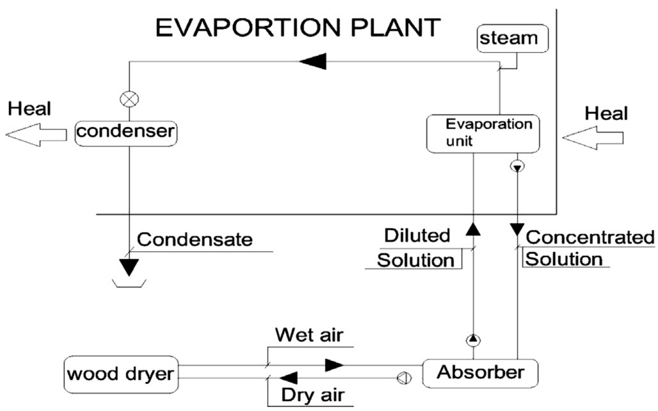


Fig. 2. Open absorption system installed at sawmill [48].

In the clay brick production process, initially, the wet clay brick contains almost 20–25% (wet basis) moisture, whereas during the preparation for insertion into the kiln, it has approximately between 8% and 12% (wet basis) moisture content. Regarding the latent heat and the difference in temperature between the brick and ambient, we can conclude that drying the brick in the brick production process requires approximately 100 kcal/kg brick, that is, approximately 19% of the total required energy to produce bricks [39,40].

2.1.3. Cement

Approximately 12–15% of the total industrial energy consumption is used in the cement subsector. In the cement manufacturing process, raw materials are accurately combined to produce Portland cement. The cement clinker consists of appropriate amount of calcium, silicon, aluminum, and iron. In the dry cement manufacturing process in which the raw mix is almost dry, approximately 20% of moisture (by mass) exists in the mixture. Nevertheless, in the wet process, the raw mix is combined with water to form slurry before transferring to the kiln. The energy saving measures in the cement industry were investigated in some sectors of cement manufacturing where the possibility of reducing and consequent optimization of the energy consumption exists. They are as follows:

- optimization of the grinding energy usage;
- use of high-efficiency classifier;
- waste heat recovery;
- use of waste heat recovery steam generator;
- use of waste heat to preheat the raw materials;
- heat recovery from the kiln surface; and
- Optimization of the cement plant heat source conditions for power generation.

Solar energy use in the cement industry can be achieved via solar kiln, which has some advantages and disadvantages. Solar kiln can be used simply and can be insulated with natural air circulation. The dryers can automatically improve the thermal efficiency and can use renewable energy, hence saving energy. On the other hand, this process and its construction are complex. In the cement industry, the required heat for drying the raw materials before putting them to the kiln is supplied by a preheater where the energy is provided by the hot exhaust gas of the kiln [41]. Table 6 shows the energy required for the equipment in a typical process of wetting and drying [42].

A study on the energy balance of a cogeneration system in a cement plant in Indiana was conducted, and the result showed that approximately 35% of the input energy was lost with the waste heat streams. Among this amount of wasted energy, between 5% and 10% could have been used for the dehydration of raw materials [43].

2.1.4. Wastewater treatment

Undoubtedly, water is one of the most important factors in the socio-economic development and in human daily comfort. As the world population increases, water consumption increases. Statistical information shows that the distribution of water around the world is not homogeneous. Whereas some countries such as the European countries consume nearly 3000 m^3 per year for each inhabitant, the consumption in the developing countries reaches 200 m^3 per year and even decreases to 20 l per day in some countries such as Mali and Haiti. Statistical data show that 70% of the produced water in the world is used in agriculture, especially for irrigation, and 30% are used in the industries. This fact implies that a large amount of wastewater is produced when water is used for any purposes and, in some cases, may be noxious and poisonous to the environment. Therefore, wastewater must not simply be abandoned, and a solution such as wastewater treatment plant should be developed to produce drinkable water from wastewater as well as other water with lower quality for gardening, cleaning uses, cooling, and other industrial demands. In all cases of wastewater treatment, the drying process is considered a basic stage after the mechanical dewatering, which may be done by filtration or centrifugation [44]. Dewatering up to 35% of solids and sanitary landfilling have been indicated as the most common form of sludge disposal [45,46]. Water that contains sewage sludge can simply be removed to a certain extent, and further moisture can be expelled by drying and thermal process. After this process, the dry solid content in the water can be reduced to less than 5%; this type of sewage sludge has lower mass and volume and, consequently, the cost of storage, handling, transportation, and landfilling will be reduced [44].

The other type of wastewater that requires treatment is olive mill wastewater (OMW). The OMW drying process, which uses an indirect type of natural convection solar dryer, is presented for energy–exergy analysis [4]. OMW is produced when vegetable water and fresh water are used in the extraction of olive oil from the plant. OMW contains olive pulp, mucilage, pectin, residual oil, and different dissolved mineral salts [47]. The production of more olive oil in the industry, especially in the southern regions of Europe, such as Spain, causes environmental problems because of the large amount of sludge and OMW. For example, the total amount of olive processed in Spain reaches an approximately 5.5×10^6 t, which generates 4×10^6 t/year of wastewater [4]. Thus, the drying system plays a significant role in such areas to reduce the volume, weight, and size of OMW and in mitigating the environmental effects and cost of storage, handling, transportation, and sanitary landfilling [44]. Many drying systems function directly with fossil fuels or with the aid of combined heat and

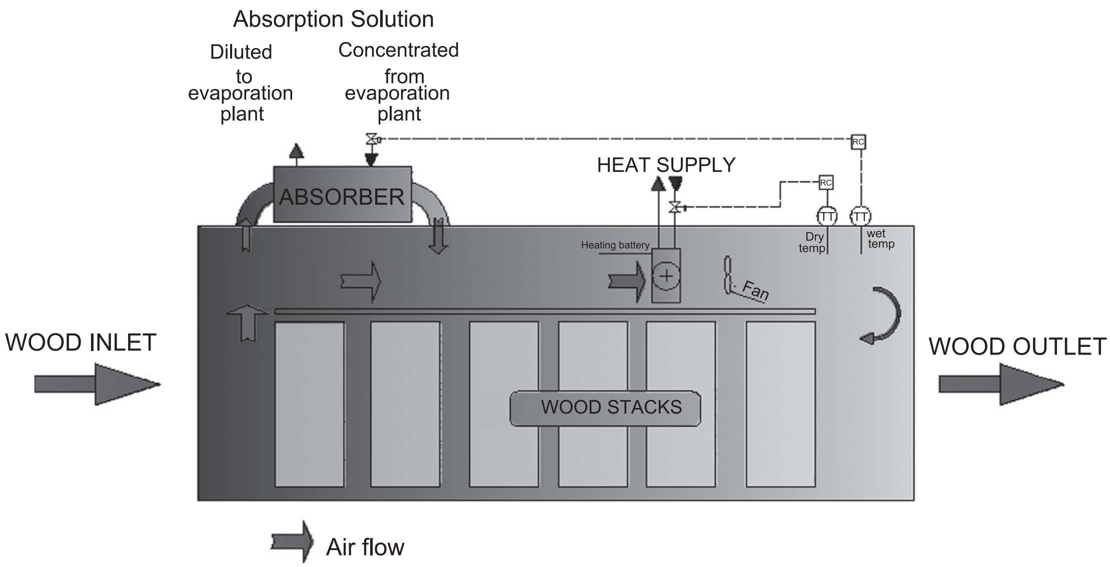


Fig. 3. Wood dryer with absorber installed [48].

Table 7
Range of approximate energy uses for drying lumber, veneer, and particles [69].

	MC (%)		Energy use	
	Initial	Dry	MJ/kg H_2O (Btu/lbH_2O)	Other
Lumber				MJ/m^3
Douglas fir	45	15	4.7–7.0 (2000–3000)	540–800
Southern yellow pine	100	12	3.7–5.1 (1600–2200)	1350–1800
Red oak	80	6	7.0 (3000+)	6.5
Veneer for plywood				MJ/m^3,10 mm (MBtu/ft^2, 3/8in)
Douglas fir	45	5	4.7–7.0 (2000–3000)	450–670
Southern yellow pine	100	5	3.7–5.1 (1600–2200)	900–1250
Particle board				MJ/m^3, 20 mm (MBtu/ft^2, 3/4 in.)
Dry wood residues	25	5	4.7–7.0 (2000–3000)	490–760 (1.1–1.7)
Wet wood chips	100	5	3.7–5.1 (1600–2000)	1900–2320 (4.2–5.2)
Green chips	100	5	4.7–5.8 (2000–2500)	2320–2900 (5.2–6.5)

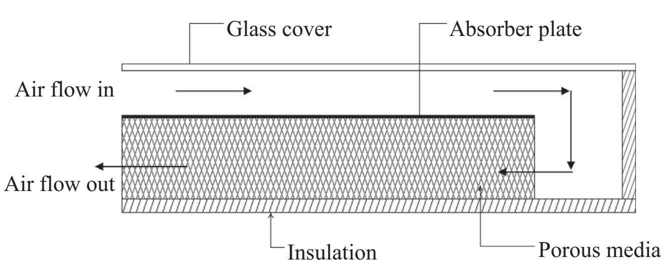


Fig. 4. The schematic of a double-pass solar collector with porous media in the second channel [49].

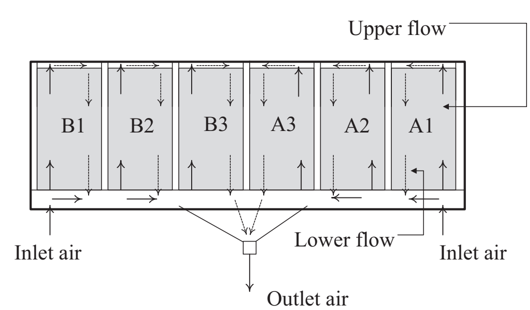


Fig. 5. The collector arrangement for the solar drying system [49].

power (CHP) processes. CHP processes are utilized to enhance the efficiency of plants; however, applying solar drying may have long pay back periods. Therefore, substituting the solar dryer in this case is difficult [48].

2.1.5. *Wood and timber*

The utilization of renewable energy in the industrial sector has not achieved a remarkable level compared with the other sources of energy such as fossil fuels. Nevertheless, in some industrial applications such as the drying system for timbers, the solar dryer system has been advanced [49]. One of the most important applications of drying is in the wood and timber industry. For example, when timber is to be used for a certain purpose such as for furniture or fuel, it must be dried because the substantial amount of water present in the green timber engenders potential problems, such as shrinking and changes in the shapes, or the timbers will be difficult to burn [50]. For simplicity and economy, solar timber driers, particularly the simple greenhouse type, are an appropriate technology for major energy savings in the developing countries. Johansson and Westerlund [51] suggested that

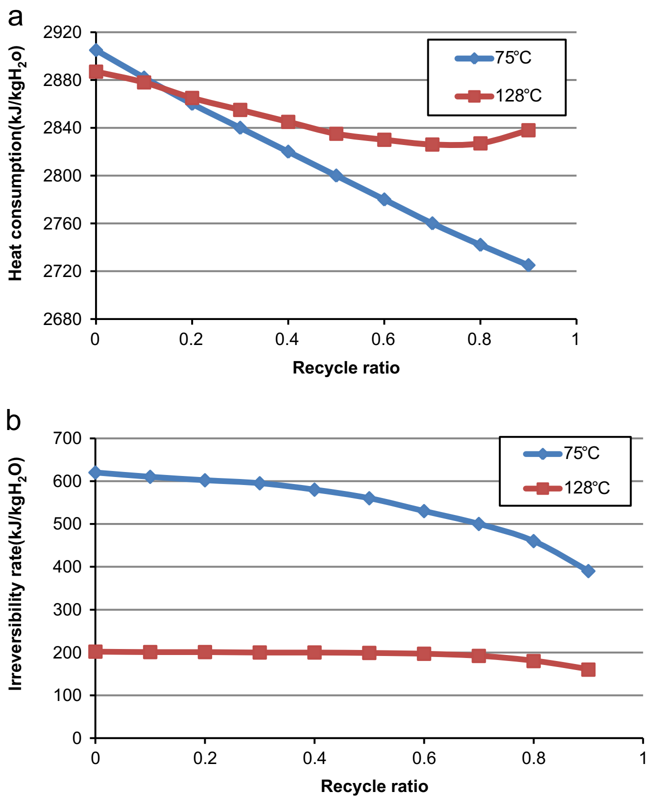


Fig. 6. (a). Heat consumption for single-stage-drying with partial recycle of spent air [24] and (b) irreversibility rate for single-stage-drying with partial recycle of spent air [24].

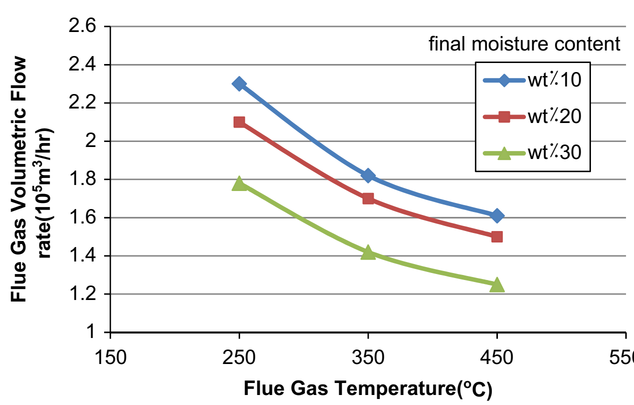


Fig. 7. Flue gas flow rates versus gas temperature for drying pine wood chips with 60% (wet basis) initial moisture content [70].

approximately 10% of the energy consumption in the Swedish industry comes from various drying processes. These processes use the open absorption system technique to recover the evaporation heat lost with the moisture in the evacuated air because of the low temperature level. Figs. 2 and 3 show the components of and a wood dryer system pilot plant, respectively.

The energy consumption in solid products is approximately 10% to 15% of the total energy usage in the main industrial sectors in Europe [52,53]. The energy consumption in wood drying is approximately 40–70% of the total energy in the wood product industry. In any wood dryer, energy is required to evaporate the water, raise the temperature of the dryer air, wood, and water to the operating temperature of the dryer, and replace the heat lost dissipated to the ambient. Based on the physical characteristics of the wood products to be dried, the drying process and efficiency of the dryer are determined. The amount of energy for drying solid

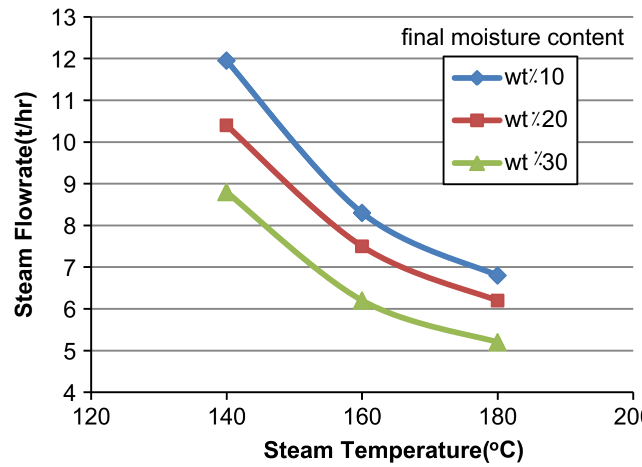


Fig. 8. Steam flow rates at different temperature for drying wood with 60% (wet basis) and steam flue gas temperature of 250 °C [70].

wood and timber products is approximately 1.5–3 times more than the heat of vaporization of pure water, that is, 2.3 MJ/kg (1000 Btu/lb). Table 7 shows the range of estimated energy required for drying lumber, veneer, and particles [54].

2.1.6. *Biomass fuel*

Biomass is a biological material derived from living or recently living organisms. Biomass can be any organic matter, such as wood, crops, weed, foliage, barks, and animal waste, and can be used as an energy source. Biomass is a well-known renewable energy source because plants and trees will continue to grow and crops and waste will always exist. Biomass as a fuel for power plants is not only very competitive in price and quality compared with fossil fuel but can also dramatically reduce CO_2 emissions. For instance, an electrical power plant that consumes coal or oil in the boilers can produce 1100 g of CO_2 per kWh, whereas the use of biomass can reduce the amount of produced CO_2 to 16 [55]. Almost 19% of the total required energy in the forest industry in Finland is supplied by barks, forest residues, and different types of waste wood [56]. These sources are by-products of the main processes and are burnt in fluidized bed boilers to produce super heat vapor for electricity generation in steam turbine generators as well as for thermal processes in the mill.

One kind of biomass is engendered from palm oil waste. Palm oil is the largest product in Malaysia, which is primarily exported to other countries. Malaysia accounts for more than 60% of the global export of palm oil. Palm oil is used in food, non-food, and pharmaceutical industries. However, a huge amount of waste product also comes from the oil processing, such as empty fruit bunches (EFB), fibers, shells, and fronds. Researchers showed that approximately 200 kg of fronds are produced per tree annually in Malaysia. Fortunately, the fronds can be converted into useful products. Drying the fronds can turn them into feeds for livestock and poultry. Figs. 4 and 5 show that, using a double-pass solar collector with porous media, the frond moisture decreases from approximately 63% to approximately 15% for a drying time of almost 7 h, whereas the system efficiency is approximately 25–30% [57,58]. Ruslan et al. [59] investigated the solar drying of oil palm fronds using a solar dryer consisting of a double-pass solar collector with finned absorber, blower, auxiliary heater, and dry chamber. This method reduced the moisture content of the fronds from 60% (wet basis) to 10% (product basis), and the collector, drying system, and pick-up efficiencies were 31%, 19%, and 67%, respectively.

Drying is a significant and challenging step in the pre-treatment of biomass for production of second generation synthetic

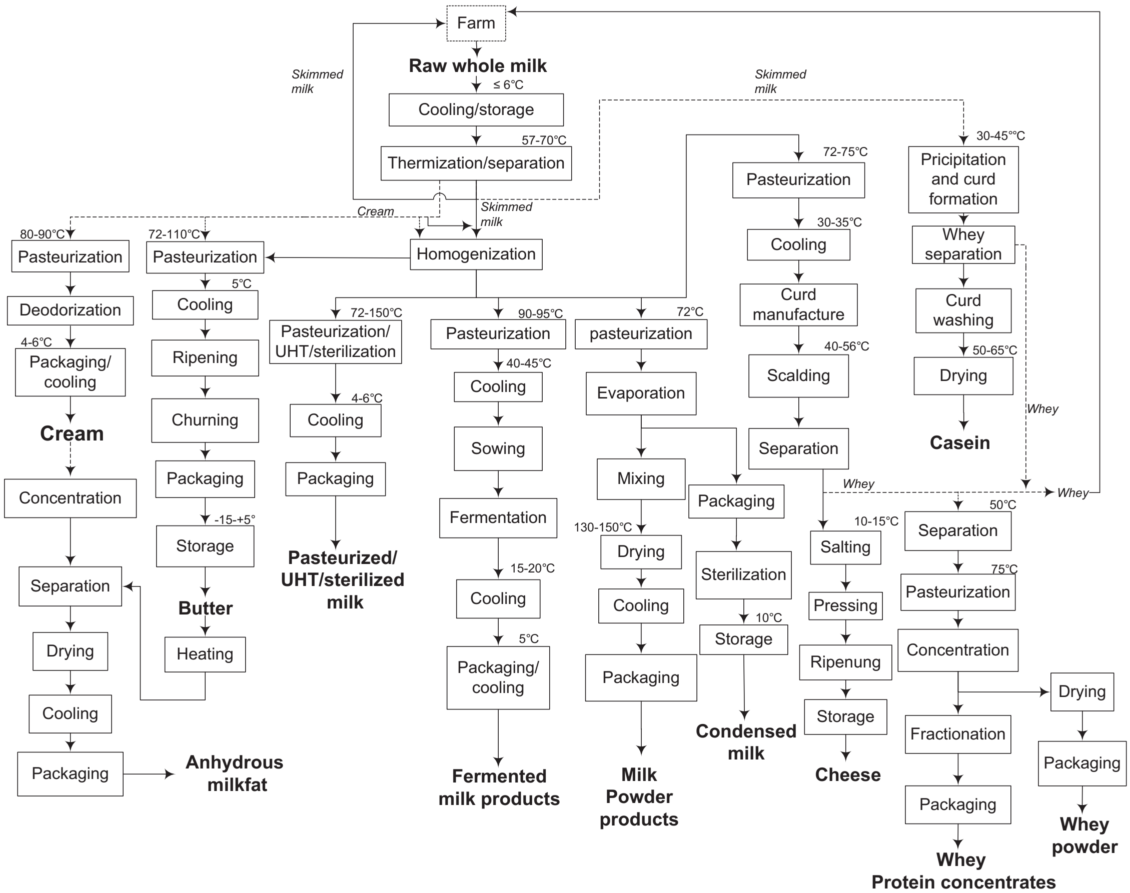


Fig. 9. The dairy industry processes [53].

fuels. The biomass feedstock is mostly wet and need to be dried from 30 to 60 wt% moisture contents to about 10–15 wt%. Important issues in drying are energy efficiency, emissions, heat integration and dryer performance. Many types of dryers or drying processes exist in industry plants [60]. An investigation has been conducted on drying biofuels such as bark, forest residual, saw dust, and chips used in fluidized bed boilers to produce heat and electricity for the mill [61]. Biofuels typically have moisture content between 50% and 60% (water per total mass). The well drying of biofuels results in the increase in electricity consumption. The heat consumption for biofuel drying for various recycle ratios is shown in Fig. 6a and b. Hanning et al. [62] investigated the integration of a drying process into a power station system. The heat source for drying was supplied using the waste heat from a process industry plant with 100 MW output. In this biomass investigation, pine chips with 60% moisture (wet basis) were dried and used as the input fuel for a subsequent 40 MW power plant. The potential thermal energy sources for the biomass drying were low-grade heat—either in the form of the flue gas from the process or as hot cooling water that could be used to form superheated steam. In their results, the amount of required energy were not clearly provided; nevertheless, the values of the flue gas volumetric flow rate in terms of the flue gas temperature and the steam flue rate as a function of steam temperature are shown in Figs. 7 and 8, respectively.

2.1.7. Dairy industry

The dairy industry covers operations pertaining to the treatment of milk for alimentary use and milk-derived products and by-products [63]. The most important dairy products are liquid milk (in various fat contents), fresh milk products such as butter and cream, different kinds of cheese, condensed milk, and dry milk products such as whey, whole milk powder, non-fat milk powder, and caseins. Drying is one of the main processes in the dairy industry. To produce milk powder, drying is an essential stage where the moisture content of the powder must reach approximately 3%. Initially, the cream is separated from the raw milk using a centrifugal separator. Then, the cream and skim milk are pasteurized at a certain temperature. The cream, as a feed material, is then moved to the next process on site, which is the butter making. The milk that enters the evaporation stage contains approximately 13% of the total solid, whereas after concentration, this amount reaches 50% before entering the spray dryer at 80 °C. In the spray dryer, 200 °C hot air is required to transform the milk into powder. The final moisture content of the milk powder is typically 3% [64]. Fig. 9 schematically shows the main processes in the dairy sector and the drying process of the milk powder, anhydrous milk fat, casein, and whey powder. One drying application is after the concentration and separation of the cream, and another is during the homogenization process to produce milk powder. In addition, drying is implemented during the production of caseins and whey powder [63].

Although energy plays a significant role in the dairy process in heat treatment during controlled bacterial growth and in prolonging the shelf life of milk and milk by-products, the energy share in the total production costs is only 1–3% [65]. Quijera et al. [49] evaluated the viability of integrating a solar thermal system to the conventional energy structure of a dairy plant in the Atlantic side of Spain. The most appropriate technology for the dairy industry is the vacuum tube-heat-pipe type because these collectors can intensively use the diffused radiation and have low coefficients

of linear and quadratic losses. Their results demonstrated the technical feasibility of replacing the thermal energy source in the dairy processing plant under the specific climate in this region using solar fields with a relatively reasonable size.

2.2. Agricultural crops drying

After harvesting agricultural products, they have to be stored, which is one of the main stages in any production. During this process, deterioration of considerable amount of the products may occur because of the existence of water in these products. Drying is a conventional method of preserving these products. In some areas around the world, some field products such as wheat, herbs, and raisins are usually spread on the ground for drying by exposure to direct sunlight. This method has many disadvantages. For example, in most developing countries like Nigeria, providing food is not a problem with regard to the production of enough crops; the problem is its inability to preserve food surplus. Present production is usually much more than the immediate needs; thus, most of the products are wasted because of the short harvest periods, and scarcity occurs during post-harvest periods. Hence, to overcome this problem, drying has been considered as the most efficient preservation technique for most tropical crops [66]. Artificial drying has been shown to be more efficient than the other methods of drying, which could not be totally managed. In industrialized countries, the energy consumption for drying is between 7% and 15% of the total energy consumption [33]. Some advantages in grain drying are the following:

- increase in the quality of the harvested grain by reducing the crop exposure to weather;
- reduction in the harvesting losses due to head shattering and cracked kernels;
- reduction in the dependence on weather conditions during harvest;
- reduction in the size and number of combined harvest equipment and labor required due to extended harvest time; and
- longer time for post-harvest field works [67].

Drying has been known to minimize losses of agricultural products from planting to consumption. Among the several methods for preserving agricultural products, increasing their economic lifespan, and providing maximum amount of nutrition level, drying is the most used and the most economical method [68]. The following benefits can be achieved using the drying system for agricultural products [69]:

- early harvest;
- planning of the harvest season;
- long-term storage without deterioration;
- advantage in higher price a few months after the harvest;
- availability of seeds; and
- better quality product.

The amount of water to be removed from crops can be calculated as

$$W_r = \frac{M_i - M_f}{1 - M_i} \tag{1}$$

where M_i and M_f are the initial and final moisture contents (in fraction) of the crop on a wet basis. Then, the useful energy required for drying a unit amount (on dry mass basis) of a crop can be obtained using the following relation:

$$UE_{dry} = \left(\frac{1-M_f}{1-M_i}\right)\ s(T_d - T_a) + \left(\frac{M_i - M_f}{1-M_i}\right)\ h_{fg} \tag{2}$$

In the above equation, the first term on the right-hand side represents the useful energy required for sensible heating of the wet crop from ambient temperature (T_a) to drying temperature (T_d). The second term represents the useful energy required for the evaporation of moisture in the crop, with h_{fg} representing the enthalpy of evaporation of water at the drying temperature. The specific heat s of the wet crop can be estimated (in MJ/kg °C) using the Siebel's formula[70].

Another expression of the useful energy required for drying a unit crop amount on a wet mass basis is suggested as

$$UE_{dry} = \left(\frac{M_i - M_f}{1 - M_f}\right)\ h_{fg} + s\,(T_d - T_a) \tag{3}$$

An energy evaluation for industrial paddy drying was performed by Jittanit et al. [71]. The energy consumption of paddy drying in a large-scale milling plant was investigated, and some experiments were conducted in the laboratory. The results indicated that the specific primary energy consumption in three drying runs was between 3.874 and 4.421 MJ/kg of water evaporated for the whole process. Motevali et al. [72] investigated the energy consumption in different drying systems, including hot-air convection, use of microwave pre-treatment with convection dryer, microwave drying, vacuum drying, and infrared drying. Pomegranate arils were chosen for testing under diverse circumstances such as different temperature and three air-velocity levels (0.5, 1, and 1.5 m/s) with three pre-treatment of the control in the case of convection drying. The following equation is used to compute the energy consumption of the pomegranate arils:

$$E_t = A\nu\rho_a C_a \Delta T t \tag{4}$$

where E_t is the total energy consumption in each drying round (kWh), A is the cross-sectional area of the container where the sample was placed (m^2), ρ_a is the air density (kg/m^3), t is the total drying time of each sample (h), ΔT is the temperature difference (°C), and C_a is the specific heat of air (kJ/kg °C). Then, the specific energy to dry 1 kg of pomegranate arils was calculated by $E_{kg} = E_t/W_0$, where E_{kg} is the specific energy (kJ/kg) and W_0 is the weight of the sample. The results showed that the energy consumption in convection drying at the maximum condition was approximately 240 kWh/kg and was reduced to 160 and 90 kWh/kg when 100- and 200-W microwave vacuum dryers were used, respectively.

An investigation was conducted in the drying of onion slices, and the total energy requirement for different inlet air temperature and airflow rate have been examined. The results showed that when the initial moisture content reached from 86% (wet basis) to the final moisture content of approximately 7% (wet basis), the energy required per unit mass removed was between 23.548 and 62.117 MJ/kg, whereas the percentage of energy contribution for heating and dehydration was approximately 69% of the total energy consumption [11]. Fig. 10 shows the variation in the energy required in terms of time at different air temperatures for a 2.43 kg/min airflow rate.

Hollick [73] conducted a feasibility study for the spices Board of India and the US/ECRE. He proposed that the commercial drying operation can be switched to solar drying with minimal change in the operation and with a payback period of 2 years. As an example, he reported that a company in Pune, India, dried sesame seeds and consumed 0.516 MJ energy to dry 1 kg of sesame seeds; for 30 t, the process required 15,480 MJ energy, whereas the efficiency of the overall drying process was 17%, considered a deficiency in such company.

3. Solar energy availability for drying

Hot air is a conventional fluid used in all drying systems, which is heated by a solar collector; thus, the amount of extracted solar

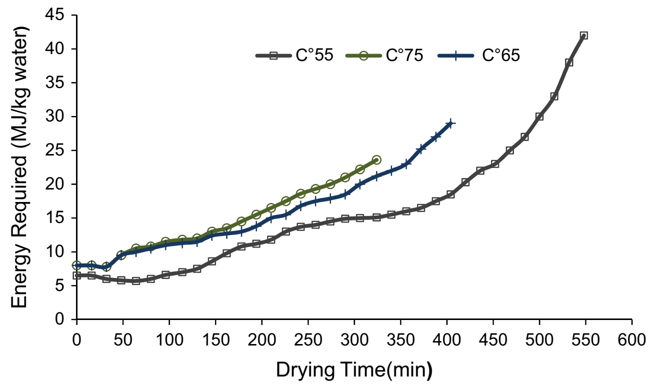


Fig. 10. Variation of energy required with drying time at different air temperatures for 2.43 kg/min airflow rate [9].

Table 8
Characteristics of non-tracking (stationary) collectors.

Types of stationary collectors	Indicative temperature range (°C)	Efficiency irradiation levels (W/m^2)		Concentration ratio
		500	1000	
Flat plate collectors (FPCs)	30–80	0.71–0.75	0.72–0.75	1
Compound parabolic collectors (CPCs)	60–240	0.45–0.73	0.58–0.72	1–5
Evacuated tube collectors (ETCs)	50–200	0.44–0.82	0.62–0.82	1

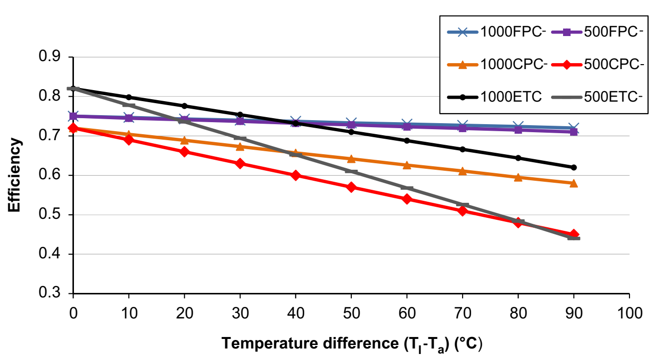


Fig. 11. Comparison of the efficiency of the three types of stationary collectors at two irradiation level 500 and 1000 W/m^2.

heat is a significant parameter in the feasibility study of whether sufficient energy is available for a specific application. Generally, the total solar energy absorbed by a solar collector can be calculated by [74]

$$Q_s = I_t(\tau\alpha) A_c \quad (5)$$

where Q_s is the rate of solar energy absorbed, I_t is the rate of incidence of the radiation for a unit area of the collector, A_c is the collector area, and $\tau\alpha$ is the effective product transmittance absorptance. Basically, $\tau\alpha$ depends on the transmittance of the transparent covers and on the absorptance of the absorbent. Solar energy for drying purposes was investigated in the literature by many researchers, particularly for agricultural purposes. Many potential fields of application are available for solar drying at the medium and medium-high temperature level (80–240 °C) [75]. Kalogirou [76] investigated the viability of a solar industrial process heat system in a Cyprus industry using the TRNSYS computer program. A simulation of the contribution of the solar processing heat plants under Cypriot environmental conditions was carried out for different collector technologies based on this software. TRNSYS can interconnect the system components in various models, solve differential equations, facilitate information output, reduce the entire problem of system simulation to a problem of identifying all the components that comprise the particular system, and formulate a general mathematical description of each component. This software obtains the total useful energy for the whole year and yields the auxiliary energy required for a certain system. Generally, the collectors used to extract the solar thermal energy in the industrial heat process can be divided into two major types: non-tracking (stationary) and one-axis sun-tracking parabolic collectors. Table 8 shows the different types of collectors used for drying purposes. The efficiency of the collectors depends on the temperature difference between the ambient and the collector inlet. A high irradiation level indicates high collector efficiency and performance as shown in Fig. 11 [72].

(1) Flat-plate collectors (FPCs).
(2) Stationary compound parabolic collectors (CPCs).
(3) Evacuated-tube collectors (ETCs).

When high temperature and more efficient collectors are desired, a high-performance solar collector is needed. The parabolic collector can provide temperature of up to 250 °C for process-heat applications. One type is produced by the Industrial Solar Technology Corporation, whose characteristics are shown in Table 9 [76].

The annual energy yield of various collectors, including the FPCs, advanced FPCs, CPCs, ETCs, and parabolic-trough collectors (PTCs), for the demand temperatures considered are also shown in Fig. 12.

The International Institute for Systems Analysis conducted a comprehensive assessment of the coordinated energy issues. Fig. 13 shows that the solar energy contribution in the industry can increase from a very small amount in 2007 to almost 6 EJ in 2050, that is, the growth is from a negligible amount to 2.7% of the total final energy demand. This projection was based on the Global Energy Assessment overall hypothesis on the infrastructure, lifestyle, and policy shown in Table 10 and based on the International Energy Agency and Energy Technology's projection in the industry. The scenarios did not include the sub-sectoral details in the industry [77].

Evrendilek and Ertekin [78] researched and reported that, whereas the difference between Turkey's total primary energy supply from the sources and the total final consumption will reach 5.71 quads in 2020, approximately 0.35 quads/year could be supplied using solar energy. Ramachandra and Shruthi [79] used the Geographical Information System to map the renewable energy potential Taluk-wise in Karnataka, India. Because Taluk is an administrative division in the federal set up in India, which uses renewable energy, they focused on Taluk-wise mapping the solar radiation to extract renewable energy. They determined that Karnataka's global radiation is in the range of 5.1–6.4 kWh/m^2 during summer, 3.5–5.3 kWh/m^2 during monsoon, and 3.8–5.9 kWh/m^2 during winter. The other study that attempted to determine the potential of solar harvesting was that by Syafawati et al. [80], which presented an analysis of the solar energy extraction potential in Ulu Pauh, Perlis, Malaysia, located at 6.462°N, 100.351°E. Their analysis is shown in Fig. 14, which shows the solar energy received from the sun either directly or as diffused or reflected sunlight. The relationship between solar

radiation and ambient temperature can also be inferred. Most of the solar radiation falls above 350 w/m^2 for 6 months, and approximately 95% of the days in the monitored period received approximately 40–70% of the total sun radiation.

Rumbayan et al. [81] determined the theoretical potential of solar irradiation in Indonesia using artificial neural networks and provided a solar map of entire Indonesia. Research works were conducted in five areas of the country, namely, Bengkula, Jakarta, Samarinda, Manado, and Ambon. Fig. 15 shows the amount of solar radiation in terms of kilowatt-hour per square meter monthly among the selected cities. They reported that the predicted results satisfactory agreed with the measured values.

Mohammadnejad et al. [82] reported the high potential of solar energy in Iran because of its geographical position, where the solar radiation varies from 2.8 kWh/m^2 per day in the north to 5.4 kWh/m^2 per day in the south. The sunshine hours are estimated to be 2800 h annually, whereas this amount could reach an average of 3200 h annually in the central part of Iran because of the hot and dry climate of this area.

4. Role of solar energy in drying systems

The effective and positive benefits derived from using renewable energy, primarily, solar energy, have been studied by many researchers [9,13,83–109]. Many advantages have been reported in the different applications of solar drying in agriculture as well as in the industry. In this study, we have considered three aspects: economical, environmental, and political.

4.1. Economical aspect

The total area of installed solar collectors reached 185 Gw_{th} by early 2010. The percentage of contribution by China, Germany, Turkey, and India accounted for 80.3%, 3.1%, 1.8%, and 1.1% respectively, and the remaining 13.7% was contributed by more than 40 countries such as the US, Mexico, Brazil, Thailand, South Korea, and South Africa. Three types of collectors, including unglazed, glazed flat-plate, and evacuated tube, are available in the market. Among the total capacity of 172.4 Gw_{th} installed until the end of 2009, the share of glazed FPCs, ETCs, and unglazed collectors were 32%, 56%, and 11%, respectively, and the remaining 1% were glazed and unglazed air collectors [83]. Sreekumar [84] conducted an economical analysis and compared the costs of solar-dried and branded products dried using other drying methods, such as dryers that used fossil fuels. Three methods were used for the economical comparison of the product costs. In the first method, the cost per unit weight of drying a product using solar dryer was compared with that of the same product that used an electrical means of drying. The cost of drying per unit weight was calculated by dividing the total annual cost by the amount of product dried in a year. One disadvantage of this method was that the cost of drying did not fully capture the economics of the solar dryer because of the cost variation during the entire life of the dryer, namely, 20 years. Whereas solar dryers use electricity for blowers and axial fans, conventional dryers need more energy to produce hot air. Thus, instead of considering a certain year to assess the economic benefits of the solar dryer, we must determine the savings over the entire life of the dryers. The second method employed this concept. Initially, the savings on drying per day of the solar dryer in the base year is determined. Then, the present worth of the annual savings over the life of the system is obtained [87]. Persuading people to use this dryer depends on the payback period. The third method, namely, payback period, requires the time to recover the initial investment. A similar approach was employed using relevant equations for economic analysis of the solar dryer for domestic use [88].

Table 9
Characteristics of the parabolic-trough collector (PTC) system [77].

Parameter	Value/type
Collector rim angle	70°
Reflective surface	Silvered acrylic
Receiver material	Steel
Collector aperture	2.3 m
Receiver surface treatment	Highly selective blackened nickel
Absorptance	0.97
Emittance (80 °C)	0.18
Glass envelope transmittance	0.96
Absorber outside diameter	50.8 mm
G_{test}—Flow rate per unit area at test conditions (kg/s m^2)	0.015
a_0—Intercept efficiency	0.762
a_1—Negative of the first-order coefficient of the efficiency (W/m^2 °C)	0.2125
a_2—Negative of the second-order coefficient of the efficiency (W/m^2 °C)	0.001672
b_0—Incidence angle modifier constant	0.958
b_1—Incidence angle modifier constant	−0.298
Tracking mechanism accuracy	0.05°
Collector's orientation	Axis in N–S direction
Mode of tracking	E–W horizontal

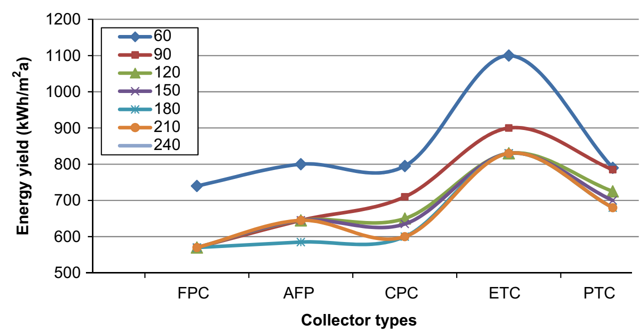


Fig. 12. Annual energy yield of collectors at different demand temperatures considered [77].

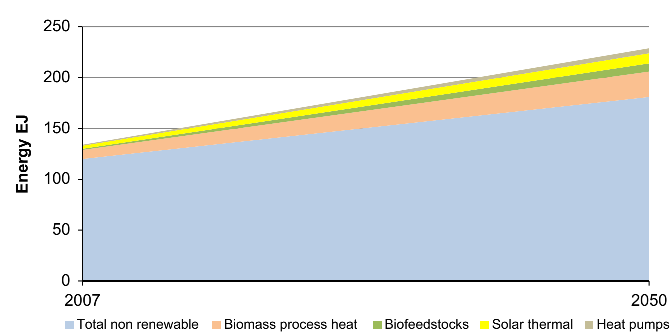


Fig. 13. Renewable potential in industry by 2050—final energy and feedstock. UNIDO analysis [78].

An economical analysis of a dryer was performed based on the economic situation in India. The analysis was done using the three aforementioned methods. In the first method, the total amount of dried products processed annually by the solar dryer was 6666.66 kg, and the cost of drying 1 kg of pineapple slices was Rs. 11 (US$1 = Rs. 45) for the solar dryer and Rs.19.73 for the electric dryer. From the second method, the cost of drying 1 kg of

Table 10
Global energy assessment scenario assumptions (IIASA, in preparation) [78].

	GEA-L	GEA-M	GEA-H
Infrastructure	Decentralized-renewable, limited nuclear, emphasis on "intelligent grids"	Regional heterogeneity in technological choice	Centralized, supply-orientation, e.g., CCS, Nuclear, large-scale renewable
Lifestyles	Major transformation in consumer choices, large uptake of demand savings measures, mass transit systems	Supply and demand side measures	Less emphasis on "dematerialization". Continued reliance on individual mobility
Policy	More re-regulation; subsidies, new business models, "feed-in" tariff equivalents in end use	Mix of policy "balanced" markets, measures across the energy system	Centrally regulated "feed-in" tariff for generation

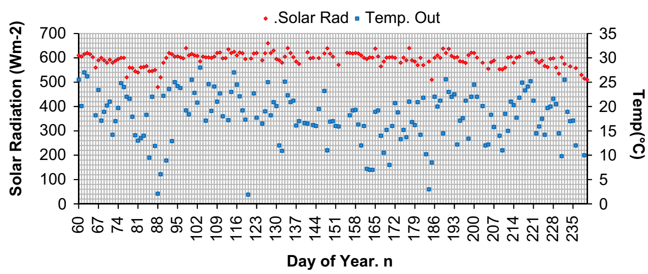


Fig. 14. Relationship between temperature and solar radiation recorded by weather station [81].

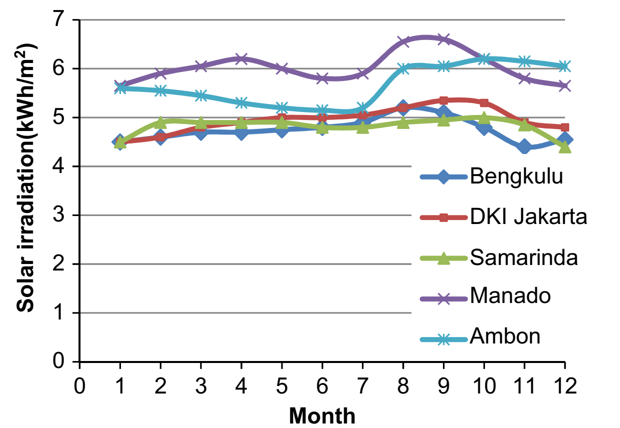


Fig. 15. The comparisons of predicted values of the monthly solar irradiation among the selected cities (Bengkulu, Jakarta, Samarinda, Manado, Ambon) [82].

pineapple slices by solar and electric dryers was calculated. Table 11 shows that the cumulative present worth was approximately 17 million rupees. Thus, the investment on solar dryer was Rs. 550,000, and roughly 17 million rupees was saved. These results were obtained under the assumption that the life span of the dryer is 20 years; however, the savings was obtained over the extended life of the system. In the third method, the payback period was calculated. Payback period is defined as the duration of the cumulative fuel savings that is equal to the initial investment. The payback period was determined to be only 0.54 year, that is, equivalent to 191 drying days, and this is a very short time compared with its lifespan.

Solar dryer defines the unit cost of the solar crop drying (UC_{dry}) as the ratio of the total expenses during a year to the amount of dried crops. It is expressed as [89,93]

$$UC_{dry} = \frac{f_{es}\, UE_{dry}\, p_c\, (CRF_{d,T} + m)}{365\, CUFI\eta_d} \tag{7}$$

For operation and maintenance, $CRF_{d,T}$ represents the capital recovery factor, which is defined as

$$CRF_{d,T} = \frac{d(1+d)^T}{d(1+d)^T - 1} \tag{8}$$

where d is the discount rate and T is the lifetime of the solar dryer. UE_{dry} is the useful energy required for drying a unit amount of crop and is determined based on the dry or wet mass [Eqs. (2) and (3)]. f_{es} is the fraction of useful energy requirement for drying supplemented by solar energy. *CUF* is the capacity utilization factor of the solar dryer, η_d is the thermal efficiency of the solar dryer, and I represents the design value of the daily solar radiation.

Hollic [73] performed an economical analysis of crop solar drying and estimated the total cost of the solar dryer as 3,200,000 Indian rupees (US$1 = Rs. 45). The fuel savings was 0.5 l/m^2 panel per day, and the annual fuel consumption was 168,000 l of oil. The price per liter of fuel was Rs. 9; thus, the savings is Rs. 1,512,000 per year, and the payback period is approximately 2 years. This payback analysis shows a good return in using the solar energy for solar drying. The calculated payback period was based on the solar panel costs, and the expenses for the complete dryer system were not considered. If the total cost of a new solar dryer project is evaluated, the other advantages such as improved quality, higher yields, and less land use should be included in the analysis to obtain more accurate cost–benefit analysis.

Table 11
Economics of the solar dryer—annual saving, present worth of annual saving and present worth of cumulative annual saving for each year during the life of the solar dryer for drying pineapple and 250 days of use of solar dryer [85].

Year	Annualized cost of dryer (US$)	Annual savings (US$)	Present worth of annual saving (US$)	Present worth of cumulative saving (US$)
1	1460	23,800	22,000	22,000
2	1460	25,000	31,400	43,600
3	1460	26,400	20,800	64,400
4	1460	27,200	20,200	84,800
5	1460	29,000	19,800	104,600
6	1460	30,400	19,200	123,800
7	1460	32,000	18,600	142,400
8	1460	33,600	18,200	160,600
9	1460	35,200	17,600	178,200
10	1460	37,000	17,200	195,400
11	1460	38,800	16,600	212,000
12	1460	40,800	16,200	228,200
13	1460	42,800	15,800	244,000
14	1460	45,000	15,200	259,200
15	1460	47,200	14,800	274,000
16	1460	49,600	14,400	288,600
17	1460	52,000	14,000	302,600
18	1460	54,600	13,600	316,200
19	1460	54,600	13,600	316,200
20	1460	60,400	13,000	342,600

4.2. Environmental aspects

Undoubtedly, renewable energy technologies plays a significant role in mitigating greenhouse gas emission and can prevent global warming by replacing fossil fuels and other related sources of energy. Nowadays, consumption of fossil fuels is dramatically growing because of improvements in the quality of life, increasing

world population, and industrialization of the developing countries. It has two main drawbacks. First, the rate of reduction of fossil fuel reserves will increase, and second, it can affect the environment, which increases health risks and the threat of global climate change. The most important factor that causes global warming is carbon dioxide, which is mostly produced by fossil fuels [90,91]. Therefore, renewable energy is a welcome alternative as a clean energy source.

Obviously, among the various renewable energy options, solar thermal energy is the most abundant and is available in both direct and indirect forms. The sun emits energy at a rate of 3.8×10^{23} kW in which approximately 1.8×10^{14} kW is received by Earth [85]. A large amount of solar energy is available for thermal application such as cooking, water heating, and crop drying, among others. In the solar drying technology of agricultural products, the process is clean and sanitary and conforms to national and international standards without paying bill for the energy. Overall, it can save energy and time, occupies less area, improves product quality, makes the process more efficient, and most importantly, it protects the environment [13].

Piacentini and Mujumdar estimated the production of carbon dioxide in a drying system [86]. They studied a drying system whose electricity energy consumption was 100 kWh/day and operated at 25 days per month and 11 months per year. Under these conditions, the estimated emitted carbon dioxide was approximately 14.77 t per year. In another study [93] on solar crop drying and CO_2 emission potential, the estimate was that a 1 m^2 aperture area of solar irradiation can prevent the production of 463 kg of carbon dioxide in the determined life cycle.

Wide distribution of the solar drying applications, especially for crops, decentralizes the application of solar energy, particularly in developing countries [9,93,96]. Ekcchukwu and Norton [9] investigated the mitigation of CO_2 emission due to the implementation of solar drying. They suggested that solar drying for cash crops such as tobacco, tea, small cardamom, coriander, seeds, and onion flakes is one of the possible areas for immediate intervention of solar energy that can reduce CO_2 emission.

4.3. Political aspects

Today, because of the obvious importance of protecting the environment, governments and industries worldwide are continuously finding ways to mitigate greenhouse gas emission. They focus on renewable energy resources, particularly solar energy [8]. Governments address the issues of energy development by establishing energy policies, along with the development of the energy industry to support its growth, including energy production, distribution, and consumption. The focus of the energy policy includes legislation, international treaties, and incentives to investors. Government policies can considerably mitigate the effects of global warming and energy crisis due to energy resource deficiency [110,111]. A comparative study of the worlds' total installed solar energy capacity from 2008 to 2009 shows a growth rate of 46.8% in which the amount of exploited energy was 22,928.2 MW in 2008. Policies such as feed-in-tariff (FIT), renewable portfolio standard (RPS), and incentives implemented by many governments around the world can provide great motivation and interest in using solar technology such as in drying in some industries. No specific model is established to achieve this goal, and every country can have its own particular policy. Various policies such as FIT, RPS, tax credit, pricing laws, production incentives, quota requirements, and trading systems, can be implemented [97,112]. Solangi et al. [94] reviewed the solar energy policies in some countries, including the US, Canada, Germany, Spain, France, China, Pakistan, Australia, and Malaysia. They revealed that, depending on the situation, each country pursues policies to persuade industries as well as the society to use solar energy as a clean, green, and free energy as much as possible. Most of the policies aim to facilitate the use of various electricity generation mixes, reduce state reliance on fossil fuel, increase renewable energy deployment, reduce carbon emission, or a combination of the aforementioned. One method to provide motivation is to mitigate tax credit, which had been subjected to many changes over the last three decades. The production of tax credit was modified several times, and what was once consistent is now [94,98].

The Department of Energy (DOF) in the US aims to generate 10–15% of the nation's energy from solar sources by 2030 [113]. Reports show that the policies implemented in the US are RPS, formation incentives, and production tax credit. The Canadian government has implemented new policies on taxation, energy, trade, labor, intellectual property rights protection, regulation, infrastructure and research development, and commercialization for the manufacturing and processing sectors to enhance the foundation of sustainable long-term economic growth [94]. Germany pursues two policies: FIT and incentives. The mechanism of FIT in the country is determined within the duration of 20 years, and a constant reward is provided for energy production. Various FITs are paid for different rated generation systems. Incentives and beneficial credit terms provide additional support [114].

France has established an extensive plan to increase the share of energy from renewable resources to 23% by 2020. Similar to Germany, France has two main policies, namely, FIT and incentives. FIT was established in July 2006. FIT obligates users to purchase electricity generated by renewable energy producers in its service area and to pay a tariff determined by public authorities and guaranteed for a specific time period. As an incentive, some forms of additional support are provided by the government [100]. China exhibited a double-digit rate of economic growth in the past two decades. This rapid growth entailed huge amounts energy consumption and a significant environmental impact [101]. China has a high potential for solar power application. The National People's Congress passed the Renewable Energy Law (REL) in 2005, thereby opening a new stage of renewable energy development in China [102]. Subsequently, numerous supporting regulations and guidelines were considered to implement REL. The National Development and Reform Committee (NDRC) identified three priorities for renewable energy development in 2006. The first is to support renewable electricity generation, including wind, solar, and water. The second is to study energy resources as an alternative for oil, and the last is to provide incentives for the use of solar energy in buildings. More laws and regulations were reported by Wang [103].

Pakistan is a country where all types of renewable energy can be exploited. Despite having a huge solar energy potential, the lack of technical knowledge renders existing systems in this country nonoperational. To address this situation, the Pakistan Council of Renewable Energy Technology (PCRET) began to ensure the development and sustainability of solar and other renewable energy projects in the country. The Alternative Energy Development Board (AEDB) joined such effort in [104]. Aside from other sporadic departments operating in this field, Pakistan has two other full-fledged departments. PCRET and AEDB aim to accelerate the development of renewable energy technologies [105]. However, only a few reports pertaining to RETs and solar energy harvesting, particularly for agricultural applications, have been presented. Sheikh presented a number of suggestions to develop, disseminate, and obtain efficient renewable energy [106]. The suggestions include formulating adequate laws to encourage investors, tax rebate, commercial and grid-connected RET projects, improving the quality of installation and technology used, supporting honesty and dedication instead of personal benefits, developing human resources, and establishing RET plants in the country. FIT,

subsidies, and emission reduction are the issues considered to promote renewable energy commercialization in Australia. The level of greenhouse gas emissions per capita is extremely high in Australia compared with other industrialized countries because of the large amounts of domestic reserves of coal that make electricity generation inexpensive. Australian policymakers established a mechanism to increase the proportion of emission-free renewable energy as well as to prevent the production of more GHGs. In 2001, Australia introduced the first national renewable energy market that employs tradable certificates.

Another country that was considered is Malaysia. By 2020, electricity generation is expected to reach 23,099 MW. In 2010, the total installed capacity was 20,493 MW, 47% of which is the energy reserve margin for peninsular. The total energy demand is shown in Fig. 16 [107]. Malaysia hopes to become a developed country by 2020 by improving various parameters, including social, environmental, and economic, and eliminating subsidies for non-renewable energy sources. One of the current policies implemented by the Malaysian government is to involve research institutions and universities in the improvement of energy research and development. Many institutes and universities, including SIRIM Berhad, University of Malaya, University Putra Malaysia, University Sains Malaysia, and University Kebangsaan Malaysia, are currently performing research on this area. Solar energy is used for applications such as domestic hot water systems, water pumping, and drying of agricultural products at present. Environmental arguments alone are not sufficient to motivate public acceptance. The appropriate support mechanism must be established to create the market, and the prohibitive pricing of RE must be eliminated to encourage businesses to adopt the technology [94]. Malaysian government provides subsidies for NG to PETRONAS. Studies have revealed that subsidies for conventional energy use should be gradually removed or transferred to RE to level the playing field; the same subsidies should be given to RE for the time [94,108,109].

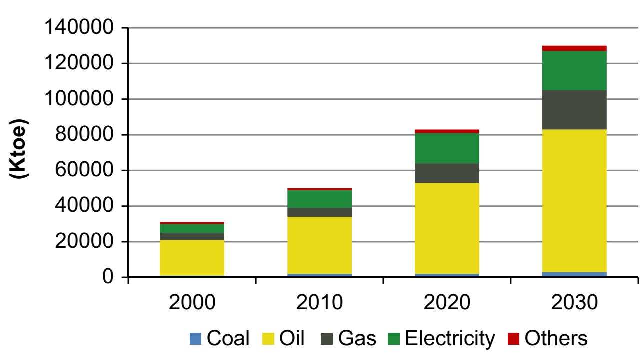


Fig. 16. Total energy demand in Malaysia (ktoe).
Source: Preliminary Energy Outlook, PTM [106]

Table 12 shows some countries' policies about solar energy in brief.

5. Future direction

Many studies have tried to exploit solar energy for drying of agricultural crops, and many researchers have presented their theoretical, empirical or semi-empirical results. Solar energy as an energy source for drying purposes in industries is not overly expected, and high potential on improving the knowledge in industrial drying exists. Industrial processes such as cement production, textile process, dairy process, clay-brick production, wood and timber process, bio-fuel drying, wastewater treatment, OMW treatment, drying of waste products of palm oil, and food preservation can employ solar energy for drying as one important part in their processes. The drying system for industrial purposes should be precisely studied based on energy and exergy analysis. So far, no comprehensive research on industrial solar drying has been performed; thus, further research and investigation are indispensable to identify the obstacles and barriers.

6. Concluding remarks

Drying, a basic process in the preservation of crops and in some industries, can be performed using solar radiation as the main source of energy. The amount of energy required for dryers depends on the materials to be dried as well as the technology employed. Considering the many programs of the governments and industrial sectors around the world to prevent the increase in greenhouse gas emissions to the environment, solar energy is proposed as the most promising reserve energy source. Moreover, depletion of fossil fuels will be prevented. Fortunately, many studies and reports revealed the large potential of exploiting solar radiation as a sustainable energy supply for future use.

Solar drying not only plays a significant role in keeping food and agricultural products from deterioration but also improves their quality. Studies indicate that the drying process is essential in some industries such as food, dairy, textile, sewage sludge, wood and timber, and cement industries. Hence, knowledge on energy consumption is important in evaluating whether the available solar energy is sufficient for these various applications.

Because heat energy is employed basically for drying, sensible heat must be supplied to the materials from the ambient to the drying temperature, and latent heat must be provided for evaporation of moisture in these products; therefore, the amount of energy required is related to the process to be performed. On average, 12% of the total energy used in the manufacturing process is consumed by the drying system. For instance, in the best situation in the cement industry, the specific energy consumption

Table 12
Summary of solar energy policy of different countries [93].

Country	Principle support (FIT/RPS)	Investment support (e.g., subsidies)	Financing/public loan	Target implementation	Legislation (e.g., GHGs emission)	R&D support	Strength (highlight)
USA	RPS	Yes	Yes	Yes (25% of supply, 2025)	Yes (25%, 2025)	Yes	Investment and production tax credit
Canada	FIT	Yes	Yes	Yes (12 GW, 2016)	Regulatory framework in2008	Yes	Production incentive of cent/kWh for the first 10 years
Germany	FIT	Yes	Yes	Yes (30 GW, 2010)	Yes (20%, 2020)	Yes	Electricity feed-in tariff
Spain	FIT	Yes	Yes	Yes (500 MW, 2010)	–	–	–
France	FIT	Yes	Yes	–	–	–	–
China	–	Yes	Yes	Yes (total capacity 30 GW, 2020)	–	–	Locally made components
Pakistan	–	Yes	Yes	–	–	–	–

was 65 kWh/t of electrical energy and 2.72 kWh/t of thermal energy, and the drying component was 7.8 and 0.33 kWh/t of electrical and thermal energy, respectively. Other examples show the following: textile, from 0.3 GJ/t to 0.9 GJ/t output; dairy, 190 MWh/year; wood and timber 3.7 MJ/kg to 7 MJ/kg H_2O; biofuel, 2800 kJ/kg H_2O; onion, 25 MJ/kg kJ/kg; and sesame, 0.516 MJ/kg products. FPCs, CPCs, and ETCs can be utilized to supply the required heat for drying depending on the process in the different industry sectors mentioned above.

In summary, solar energy is feasible for the drying system, including industrial processes, given the amount of energy consumed by dryers and considering that solar radiation is unlimited and available in most parts of the world at an average of 200–500 W/m^2. Solar drying has positive economic, environmental, and social effects on human life. Solar drying can mitigate monetary burdens via a payback period of one year or less than 10 years at most. Solar drying can also reduce the greenhouse effect and CO_2 production and facilitates the establishment of suitable policies in different countries.

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